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Bracht, Jürgen; Lach, Saul; Winter, Eyal

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Jürgen Bracht *
Saul Lach **
Eyal Winter **

*   University of Bristol
** The Hebrew University of Jerusalem

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Wissenschaftszentrum Berlin für Sozialforschung gGmbH,
Reichpietschufer 50, 10785 Berlin, Germany, Tel. (030) 2 54 91 – 0
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ABSTRACT

Modeling Oligopolistic Price Adjustment in Micro Level Panel Data*

by Jürgen Bracht, Saul Lach, and Eyal Winter

Consumer prices in many markets are persistently dispersed both across retail outlets and over time. While the cross sectional distribution of prices is stable, individual stores change their position in the distribution over time. It is a challenge to model oligopolistic price adjustment to capture these features of consumer markets. In belief based models of price adjustment stores react to expected profits. The expectations are based on the observed vector of market prices in the previous periods. In a reinforcement model of price adjustment, if a strategy has proven fruitful in the past, it is apt to be the strategy relied upon at the present. We collect price data on a homogeneous consumer product in Israel. We estimate the structural parameter of the models. We find that the reinforcement model describes the data better than the belief based models.

Keywords: Experiments; Information; Learning

JEL Classification: C72, C91, D83

ZUSAMMENFASSUNG

Modellierung des Preisverhaltens in oligopolistischen Märkten mit Paneldaten

Preise für viele Konsumgüter sind weit verteilt. Dies gilt sowohl für die Verteilung über die Zeit als auch für die Verteilung zwischen den Verkaufsstellen. Während die Querschnittsverteilung der Preise stabil ist, wechseln die einzelnen Verkaufsstellen ihre Position in der Verteilung über die Zeit. Es stellt eine Herausforderung dar, diese Merkmale der Märkte für Konsumgüter zu modellieren. Im Vermutungslernen bilden die Verkaufstätten Erwartungen über das zukünftige Preissetzungsverhalten der Konkurrenz. Die Erwartungen basieren auf dem vorherigen Entscheidungsverhalten der Konkurrenz. Im Bekräftigungslernen werden erfolgreiche Strategien gerne wiederholt. Preisdaten eines homogenen Gutes in Israel werden erhoben. Die strukturellen Parameter der Modelle werden geschätzt. Bekräftigungslernen beschreibt das tatsächliche Entscheidungsverhalten besser als Vermutungslernen.

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1 Introduction

Prices of consumption goods in Israel are dispersed, both across vendors at a point of time and across time at a vendor. The distribution of prices across vendors is stable, however vendors change their position in the distribution over time (Lach (2002)).

In this paper, we model the process of price adjustment of vendors. We estimate two families of adaptive models. We intend to capture the feature "persistent price dispersion", observed in each of the markets analyzed in Lach (2002).

Imagine an industry with a small number of vendors, each selling an undifferentiated good. Consumers do not care from which vendor they purchase the good. The lower a vendor's price, the more consumers will buy the product at the vendor. The vendors are rivals, and the actions (prices) of the rivals affect how well a vendor does.

In the first kind of model, each vendor makes a conjecture about the course of action of the rivals in the next period. Given this conjectures, each vendor calculates the expected profits he would obtain had he chosen prices from his choice set. The higher the expected profit of an action, the more frequently the vendor will choose that action.

In the second kind of model, each vendor assesses how profitable an action has been in the past. Profitable actions are more frequently repeated than unprofitable ones. Action similar to actions both chosen and profitable are also repeated frequently.

Heterogeneity emerges in response to the history from the way vendors dynamically update.

We estimate the structural parameters of the models. We are able to obtain reasonable estimates of the models. We find that a single reinforcement model describe behavior better than a family of belief based models.

2 Traditional models of oligopoly and a novel approach

In this section, we review standard approaches in microeconomic theory. Standard theory models individual actors, firms or consumers, and describes the behavior of the actor which is traditionally utility maximization by consumers and profit maximization by firms. An institutional framework is described: what are the options the actors have; what outcomes do the actors receive as a function of the actions of others; traditionally the price mechanism and equilibrium analysis.

In standard models of oligopoly, a finite number of firms optimize i.e. they take into account how their actions affect the prices they face both directly and, through possible reactions of their rivals, indirectly.

Various classic models of oligopoly are differentiated by conjectures that each participant makes concerning the actions of its rival. One makes assumptions about the conjectures and then finds the corresponding equilibrium outcome. An equilibrium is a point at which neither firm in the pursuit of maximal profit wishes to change its own action, given the actions that it supposes others will take if it changes its own action.

Equilibrium analysis does not specify how the equilibrium is achieved. This is a caveat as one might suspect that the actors do not have complete information about the demand of consumers and the cost structure of their competitors. Thus, it is natural to look at models of adaptation to describe and predict pricing. We model firms (vendors) and consumer. We describe a single model of consumer choice and we define two families of models of vendor choice. The two kinds of models are distinguished by the way vendors respond to historical information. In both models, vendors do not necessarily act in a way that can be described as maximizing anything at all. The vendor searches hazardously for ways in which to change. We describe the options the actors have. We describe the outcomes the actors receive as a function of the actions of others. We embed vendors in an environment where the vendors will act, interact, and change according to the behavioral models posed. In both models, vendors are not necessarily "in equilibrium".

3 Price data

The data are monthly retail price quotations for a homogeneous product obtained from the Central Bureau of Statistics in Israel; the Consumer Price Index (CPI) is computed using those kind of quotations.

The good is a durable good - a refrigerator. The good has a precise label (Amcor) and physical attributes (model, size etc.) that make it easy for the person which collects the price data at the store to identify it. We are able to ensure that the prices over time correspond to the same physical product. The product is homogeneous as far as the physical characteristics are concerned.

The data was collected in 3 cities in Israel: Haifa, Tel Aviv and Jerusalem. 348 observations were sampled over 48 months; 179 observations in 2000 and 169 in 2001. The minimum number of observation in a month is 13 and the maximum number of observations is 16[1].

115 observations were collected at 5 vendors in city 11 (Jerusalem), 121 observations were collected at 6 vendors in city 31 (Tel Aviv) and 112 observations were collected at 5 vendors in city 71 (Haifa)[2]. Vendors that are out of stock when visited by the surveyor are assigned a missing value.

The data set has 5 variables: retail price in NIS, year, month, city identification and vendor identification.

[1] In the year 2000, the sequence of the number of observations starting in January and ending in December is: $16, 15, 15, 14, 14, 14, 15, 15, 14, 16, 16, 15$

In the year 2001, the corresponding sequence is: $15, 15, 15, 14, 13, 15, 15, 13, 13, 13, 14, 14$

[2] In city 11, the number of observations by store is: $20, 23, 24, 24, 24$

In city 31, the corresponding number by store is: $19, 19, 20, 20, 20, 21$

In city 71, the corresponding number by store is : $19, 22, 23, 24, 24$

We collect descriptive statistics of the variable data in the following table:

Time Range	2000-1	2000	2001
Minimum price	3800	4200	3800
Maximum price	9926	9926	5470
Mean price	4992	5248	4720
St. deviation of price	565	593	377
25% Percentile of price	4700	4890	4500
50% Percentile of price	4963	5170	4700
75% Percentile of price	5200	5490	4992

The observation with price equals to 9926 is an outlier. We will exclude this observation when graphing the data and when estimating the behavioral models.

Figure 1 in the appendix graphs the variables price and month, for the complete set of data. It is evident that Lach's (2002) finding is uphold for our data set. Substantial dispersion of the price of a homogeneous good exists and persists. Figure 2 graphs the variables price and month sorted by the three cities. Note that the general finding of substantial and persistent price dispersion is confirmed for the three subsets. Figure 3 graphs the variables price and month sorted by each store identification. Note that Lach's (2002) finding that stores do change their position in the distribution of prices over time appears to be uphold. Note also that there is habit: The probability of observing a particular price does depend in a positive fashion on whether that price has been chosen in the previous period. Figure 4 graphs the variables price and store. Note, once again, that there is substantial price dispersion across time, for each of the sixteen stores.

Figures 5-8 graph the kernel density estimates of multivariate probability, for the complete data set and for each of the three cities. These pictures collectively make the point that there is a dependency between the price and the lagged price. The paper attempts to discover the nature of the dependence.

4 Models of oligopolistic price adjustment

Vendors post prices in each period t. We denote by s_j^i the price j set by vendor i. In this section, we present two kinds of models of vendor choice: Belief based models of price adjustment and reinforcement models of price adjustment. Both kinds of models share a common model of consumer choice. We first describe consumer choice. Second, we describe belief based price adjustment. Third, we describe adjustment of profit assessments.

4.1 Consumer choice

Let I be the set of vendors. Let S^i denote the pure strategy set of vendor $i \in I$. Let J be the finite number of strategies. Note that s_j^i is an element in S^i. Let $s(t) = (s^1(t), s^2(t), ..., s^i(t), ..., s^m(t))$ be the strategy profile actually played by the m vendors in period t.

There are n consumers with reservation prices $c_l \in C$. Consumer l chooses among the vendors whose posted price is lower than the consumer's reservation price. Consumer l's probability of shopping at a particular vendor is proportional to his surplus. Formally, if the actually posted prices in period t are given by $s(t)$, then the probability, $q_{li}(t)$, that consumer l shops at vendor i in period t is given by

$$\begin{aligned} q_{li}(t) &= 0 \text{ if } c_l < s^i(t) \\ q_{li}(t) &= \frac{c_l - s^i(t)}{\sum_{k \in L} c_l - s^k(t)} \text{ otherwise; where } L = \{i : s^i(t) \leq c_l\}. \end{aligned}$$

Note that the system of equations implies that the consumer shops at cheaper vendors with (equal or) higher probability.

4.2 Vendor choice

4.2.1 Belief based models of oligopolistic price adjustment

In this subsection, we describe how vendors form conjectures about the pricing behavior of the competition in the next period. Each vendor predict the price of each of his competitors. After each repetition of the game, the expectations are updated. We describe how vendors adjust their choice behavior according to their expectations.

Expected prices Each vendor i forms expectations about the prices vendors $-i$ (i.e. $i = 1, 2, 3, ..., i-1, i+1, ..., m$) will charge in the next period. Denote the vector of expected prices by $p^{-i}(t) = (p^1(t), p^2(t), ..., p^{i-1}(t), p^{i+1}(t), ..., p^m(t))$. The expectations are based on observed prices in the past ($t = 1, 2, 3, ..., t-1$).

We illustrate how expectations about vendor $i+1$'s pricing behavior are formed. Note that the remaining vendors hold the same expectations. Let $N^{i+1}(t)$ denote a counter of vendor $i+1$'s play. Initialize $N^{i+1}(t) = N(0)$. Let $N^{s_j^{i+1}}(t)$ denote a counter of vendor $i+1$'s play of action s_j^{i+1}. Set $N^{i+1}(t) = \sum_{s_j^{i+1} \in S^{i+1}} N^{s_j^{i+1}}(t), \forall t$. The updating equations of the counters are

$$\begin{aligned} N^{i+1}(t) &= \rho N^{i+1}(t-1) + 1, \text{ for } t \geq 1, \text{ and,} \\ \text{for each } s_j^{i+1},\ N^{s_j^{i+1}}(t) &= \rho N^{s_j^{i+1}}(t-1) + I(s_j^{i+1}(t), s_j^{i+1}), \text{ for } t \geq 1. \end{aligned}$$

where $s_j^{i+1}(t)$ denotes the action actually chosen by vendor $i+1$ in period t, where ρ denotes the discount factor of experience and $I(a, b) = 1$ if $a = b$ and 0 otherwise.

The expected frequency of play of action s_j^{i+1} by vendor $i+1$, after period t, is given by

$$k^{s_j^{i+1}}(t) = \frac{N^{s_j^{i+1}}(t)}{N^{i+1}(t)}.$$

Then, the expected price of vendor $i+1$ in period $t+1$, $p^{i+1}(t)$, is given by

$$p^{i+1}(t+1) = \sum_{s_j^{i+1} \in S^i} k^{s_j^{i+1}}(t) \cdot s_j^{i+1}.$$

Note that Cournot conjectures are a special case i.e. if $\rho = 0$, then $p^{i+1}(t+1) = s_j^{i+1}(t)$ i.e. vendor $i+1$ is expected to maintain the price posted in the previous period.

Choice behavior We denote by $s_j^i(p^{-i}) = (s_j^i, p^{-i})$ the price vector in which vendor i posts as a price s_j^i and he predicts vendors $-i$'s prices to be given by p^{-i}. Let $D^i(s_j^i(p^{-i}))$ be the expected number of consumers purchasing at vendor i posting price s_j^i, given the price vector $p^{-i} = (p^1, ..., p^{i-1}, p^{i+1}, ...\ p^m)$. Vendor i's expected profit is given by $w^i(s_j^i(p^{-i})) = D_i(s_j^i(p^{-i})) \cdot s_j^i$. The probability, $\pi_j^i(t+1)$, of vendor i playing action s_j^i in period $t+1$ is somewhat proportional to the performance of each action s_j^i with respect to period t prices. Formally,

$$\pi_j^i(t+1) = \frac{\exp(\beta \cdot w(s_j^i(p^{-i})))}{\sum_{s_k^i \in S^i} \exp(\beta \cdot w(s_k^i(p^{-i})))}$$

where β is a payoff sensitivity parameter.

Set of estimated parameters We estimate demand by determining reservation prices. Specifically, we obtain an estimate of the maximum of reservation prices. Formally, let the set of reservation prices be given by $C = \{\alpha, \alpha - g, \alpha - 2 \cdot g, \alpha - 3 \cdot g, ...\}$ where $g = \alpha/n$. We assume $n = 100$. We estimate α.

We determine the way in which expectations are formed by estimating the initial counter $N(0)$ and the discount factor of experience ρ. The initial counters for each strategy are the same for each vendor i such that

$$N^{s_j^i}(0) = N^{s_k^i}(0),\ \forall s_j^i, \forall s_k^i, \forall i.$$

Finally, we estimate the payoff sensitivity parameter β.

4.2.2 Reinforcement model of oligopolistic price adjustment

We present a reinforcement model of vendors' pricing behavior. The vendor associates with each of his strategies a subjectively assessed profit. The subjectively assessed profit represents the profit the vendor anticipates he will receive from the choice of the strategy. After each repetition of the game, vendors receive profits and update assessments of strategies. The assessments with greater similarity are updated in a more similar manner. The labelling of the strategies provides some information about the similarity among the strategies.

Let $u_j^i(t)$ be the subjective assessment of player i for his strategy j, s_j^i, at repetition t. Let $u^i(t)$ be the vector of subjective profit assessments for each of a vendor's strategies. Let $\mu_j^i(t)$ be the actual profit, given $s(t)$. To update assessments, the vendor takes a weighted average of his assessment and the profit he receives :

$$u_j^i(t+1) = u_j^i(t) + \lambda \cdot f \cdot (\mu_j^i(t) - u_j^i(t)),\ 0<\lambda<1,\ \forall s_j^i \in S^i$$

λ denotes an updating parameter. $f : S \times S \to \Re$ denotes a similarity function[3] such that, whenever the function value equals 1, the player sees the two strategies as identical, and, whenever the function value equals 0, the player sees no similarity. Specifically, $\forall s_k^i \in S^i$,

$$\begin{aligned} f(s_j^i(t), s_k^i; h) &= 1 - \frac{|s_j^i(t) - s_k^i|}{h} \text{ if } |s_j^i(t) - s_k^i| \leq h \\ &= 0 \text{ otherwise.} \end{aligned}$$

h denotes the window width. Note that we assume that the similarity function does not change over time and it is the same for each vendor.

The probability, $\omega_j^i(t)$, of vendor i playing strategy s_j^i in period t is somewhat proportional to the assessment of each strategy s_j^i. Formally,

$$\omega_j^i(t) = \frac{\exp(u_j^i(t))}{\sum_{s_k^i \in S^i} \exp(u_k^i(t))}$$

Set of estimated parameters We estimate the maximum of reservation prices, α. We assume $n = 100$. Let the set of reservation prices be given by $C = \{\alpha, \alpha - g, \alpha - 2 \cdot g, \alpha - 3 \cdot g, ...\}$ where $g = \alpha/n$.

We estimate the updating parameter λ and the parameter h, the window width.

We assume that the initial assessments are given by

$$u_j^i(0) = 0,\ \forall i.$$

4.2.3 Specification of the strategy space of the vendors

In estimation, we specialize to the set of strategies $S^i = \{2025, 2050, 2075, ..., 7000\}$, $\forall i$.

5 Estimation technique and result

5.1 Technique

One way to view the models of price adjustment is as forecasting rules that, given information from previous rounds, predict vendors' choices in the current round. We describe the maximum likelihood estimation procedure that minimizes the error of the period to period transitions. These transitions are based on the observed data on prices in the current rounds. Vendors' predicted probabilities are obtained as discussed above.

The maximum likelihood method uses a measure of closeness of predictions to actual choices: log likelihood. Each player has 200 actions. Let $D^{s_j^i}(t) = 1$ if action s_j^i is chosen

[3] This particular function is employed by Sarin and Vahid (2001).

Table 1: Reinforcement learning, Data from 3 cities in Israel, 2000-2001

City 11				
n	$-LL$	α	λ	h
115	4.7283e+02	1.1364e+04	9.5700e-06	1.6726e+01
City 31				
n	$-LL$	α	h	λ
121	4.7056e+02	8.5715e+03	9.9817e-04	2.1578e+03
City 71				
n	$-LL$	α	h	λ
112	4.8305e+02	4.0417e+04	1.5467e-05	4.8305e+02

by vendor i in period t, otherwise zero. Let $prob_j^i(t)$ denote the probability that vendor i choose action s_j^i in period t. Let T denote the length of the repeated game. Let I denote the number of vendors.

The likelihood function, the formula for the joint probability distribution of the data, is

$$L(\theta) = \prod_{i=1}^{I} \prod_{t=1}^{T} \prod_{j=1}^{200} prob_j^i(t)^{D^{s_j^i}(t)} (1 - prob_j^i(t))^{1-D^{s_j^i}(t)}).$$

In estimating the reinforcement model, let $prob_j^i(t) = \omega_j^i(t)$. In estimating the belief based model, let $prob_j^i(t) = \pi_j^i(t)$.

5.2 Estimation results

We estimate the three parameters of the reinforcement model using the maximum likelihood technique. We use MATLAB R13's optimization procedure fminsearch. 1 reports the estimation results of the reinforcement learning model on the data from the three cities in Israel during the years 2000-2001. The model fits the data equally well on data from each of the three cities. The estimates of the maximum of reservation prices in NIS are reasonable. The estimates of the updating parameter λ have the correct sign. We are most interested in the estimates of the parameter h, the window width. The parameter estimates informs us whether the vendors in the three cities see two strategies which are 'close' as similar.

For Jerusalem, the estimate of h is 16.73. The value means that assessments of all strategies which are very close (in a range of 400 NIS) to the strategy actually chosen are updated. For Tel Aviv and Haifa, the estimates of h indicate that all strategies in the strategy set are updated after each repetition of the game.

We estimate the four parameters of the family of belief based models using the maximum likelihood technique. We use MATLAB R13 procedure fminsearch. The data is fit poorly by the belief based models; convergence of the optimization procedure is very slow such that some doubt is cast on the reliability of the results obtained. Nevertheless, 2 reports the estimation results of the model on the data from the two cities in Israel during the years 2000-2001.

Table 2: Belief based learning, Data from 3 cities in Israel, 2000-2001

City 11					
n	$-LL$	α	λ	ρ	$N(0)$
115	5.8180e+02	1.8157e+04	1.3228e-05	5.7129e-01	9.9220
City 31					
n	$-LL$	α	λ	ρ	$N(0)$
121	6.0172e+02	1.9656e+04	1.70821e-05	1.2850e+00	-1.9912

With the caveat in mind, we note that estimates of the maximum of reservation prices are reasonable. The estimates of the payoff sensitivity parameter β have the correct sign. The estimates of the initial counter $N(0)$ for city 11 indicates that little weight is given to experience obtained prior to play. The estimates of $N(0)$ for city 31 has the wrong sign. The estimates of the factor ρ for city 11 indicate that experience is discounted at a rate somewhat between Cournot ($\rho = 0$) and Fictitious Play ($\rho = 1$). The estimates of ρ for city 31 indicates that as play progress more and more weight is give to prior experience.

6 Conclusion

There is a growing literature in experimental economics on models of adaptation in game situations. Collectively, these paper make the point that models of adaptation go a good way describing human behavior in laboratory game situations. To name just three papers, research in this direction is reported in Erev and Roth (1998), Feltovich (2000) and Sarin and Vahid (2001).

In this paper, we model human behavior observed in the field. Note that we, as econometricians, do not know the structure of the game, but we have to estimate the structure of the game being played. Consequently, our task is more complicated than the task of an econometrician analyzing typical laboratory data. This paper explores a new domain; there is very little research upon which to build an empirical model of pricing behavior.

The econometrician might not be able to know the true structure of the game, but neither might the players themselves. For instance, the players might have very little or no information about the strategy set and payoff function of their competitors.

Our behavioral models do not require that players have much information. This is an appealing feature. In the reinforcement model, players need to know their strategy set and the actual profit realized by chosen strategies. In the belief learning models, players need to know their strategy set, the actual choices of their competitors and their own payoff function.

Our results while preliminary indicate that actual play is in accordance with reinforcement learning.

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Appendix 1: Figures

February 4, 2003

Figure 1: Graph of variables price and month

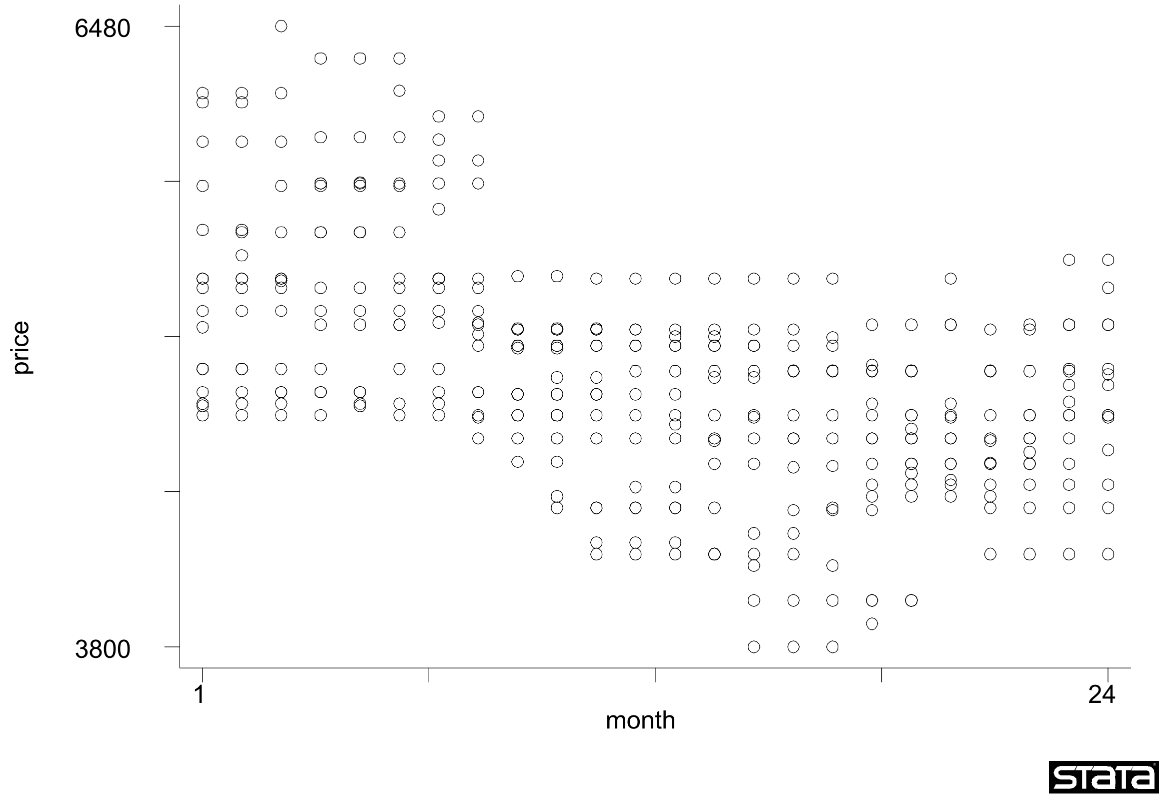


Figure 2: Graph of variables price and month by city

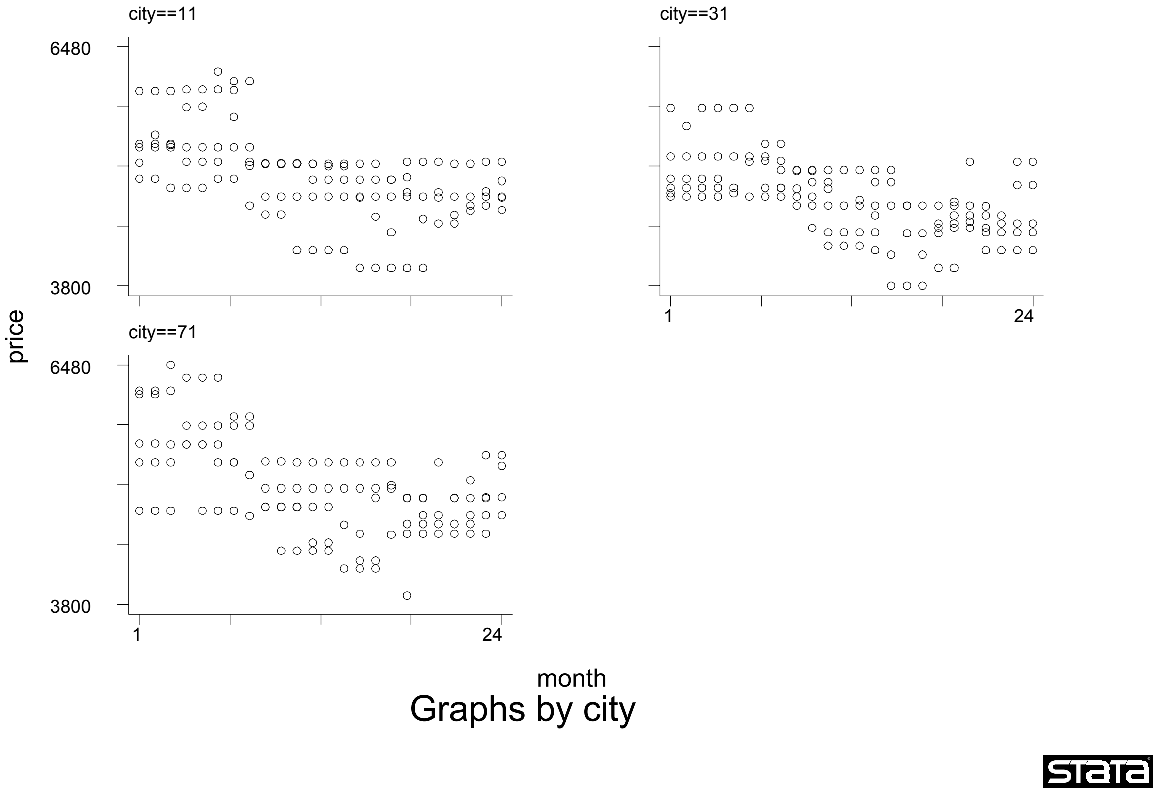


Figure 3: Graph of variables price and month by store

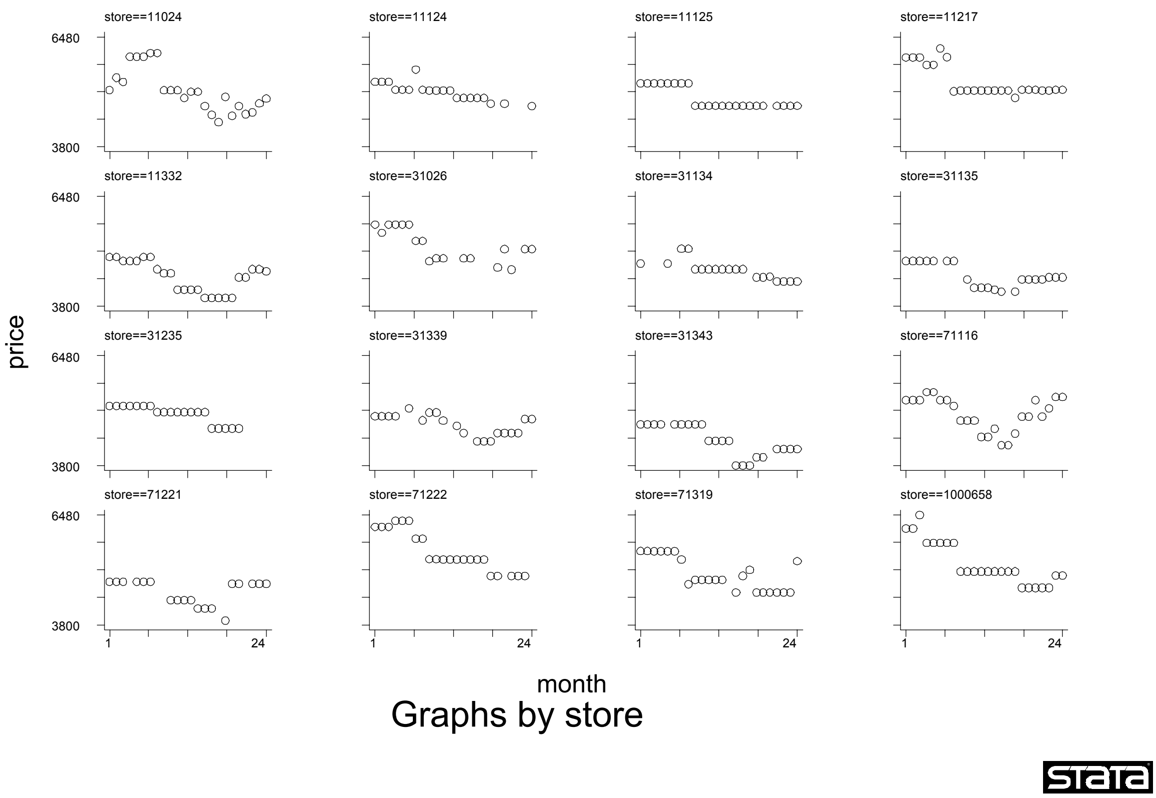


Figure 4: Graph of variables price and store

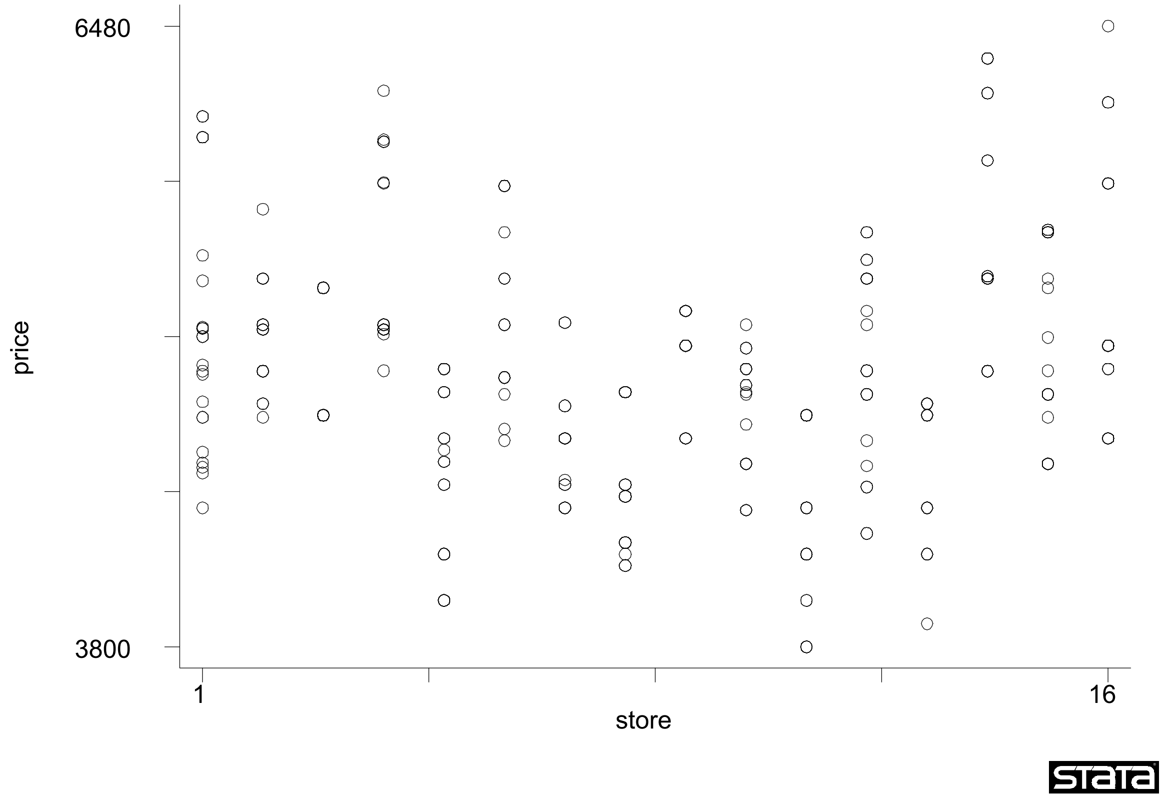


Figure 5: Graph of kernel density estimates of multivariate probability

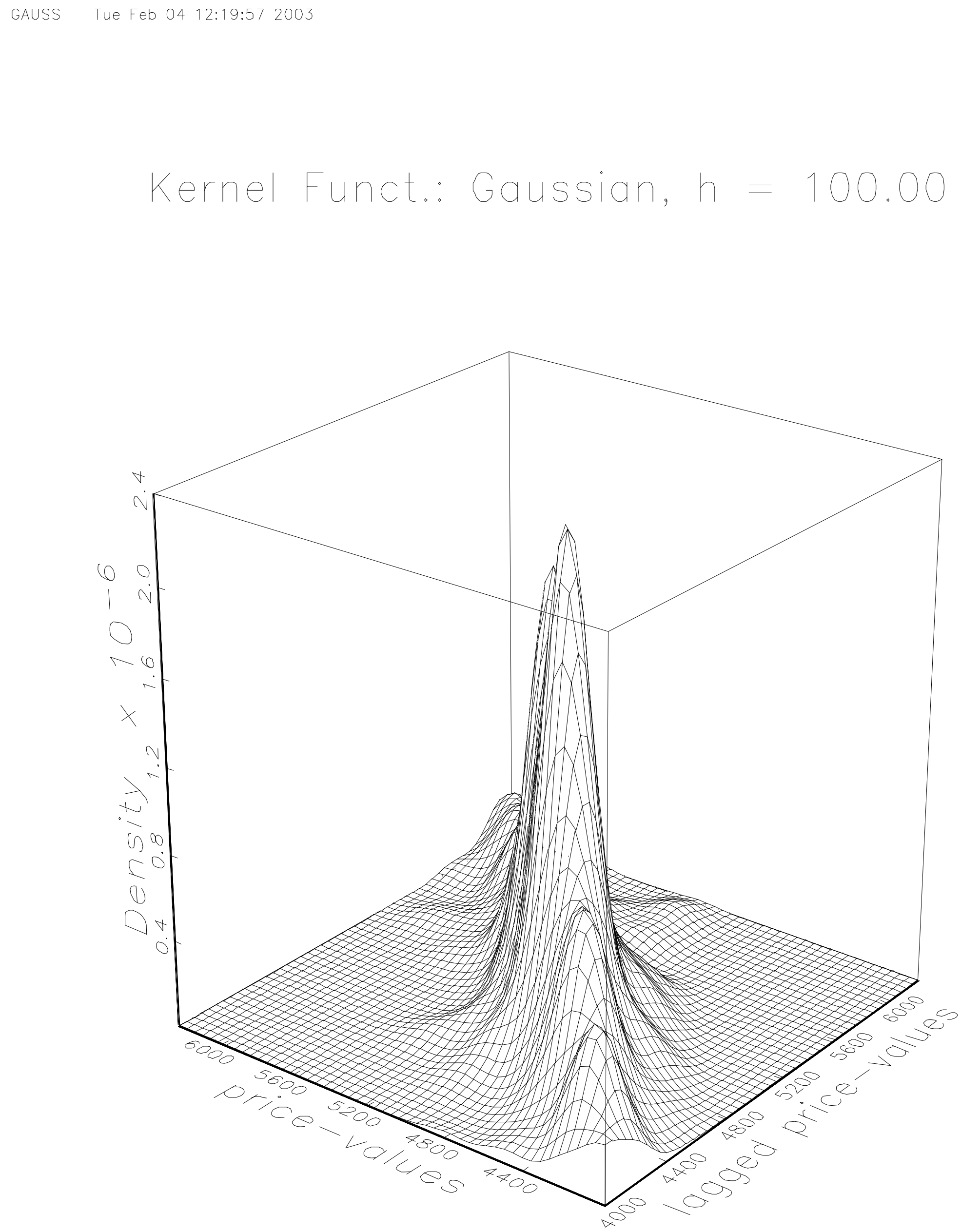


Figure 6: Graph of kernel density estimates of multivariate probability

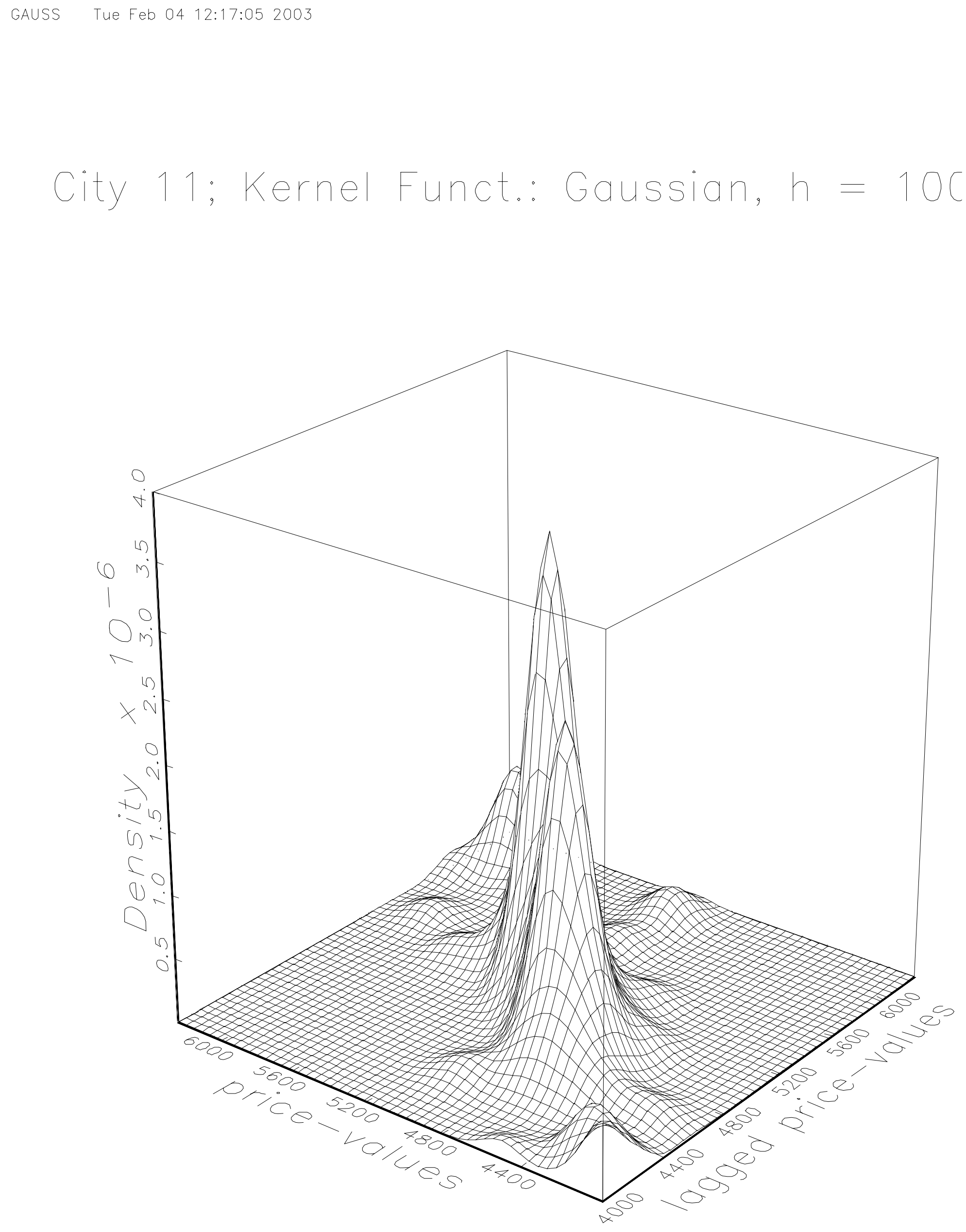


Figure 7: Graph of kernel density estimates of multivariate probability

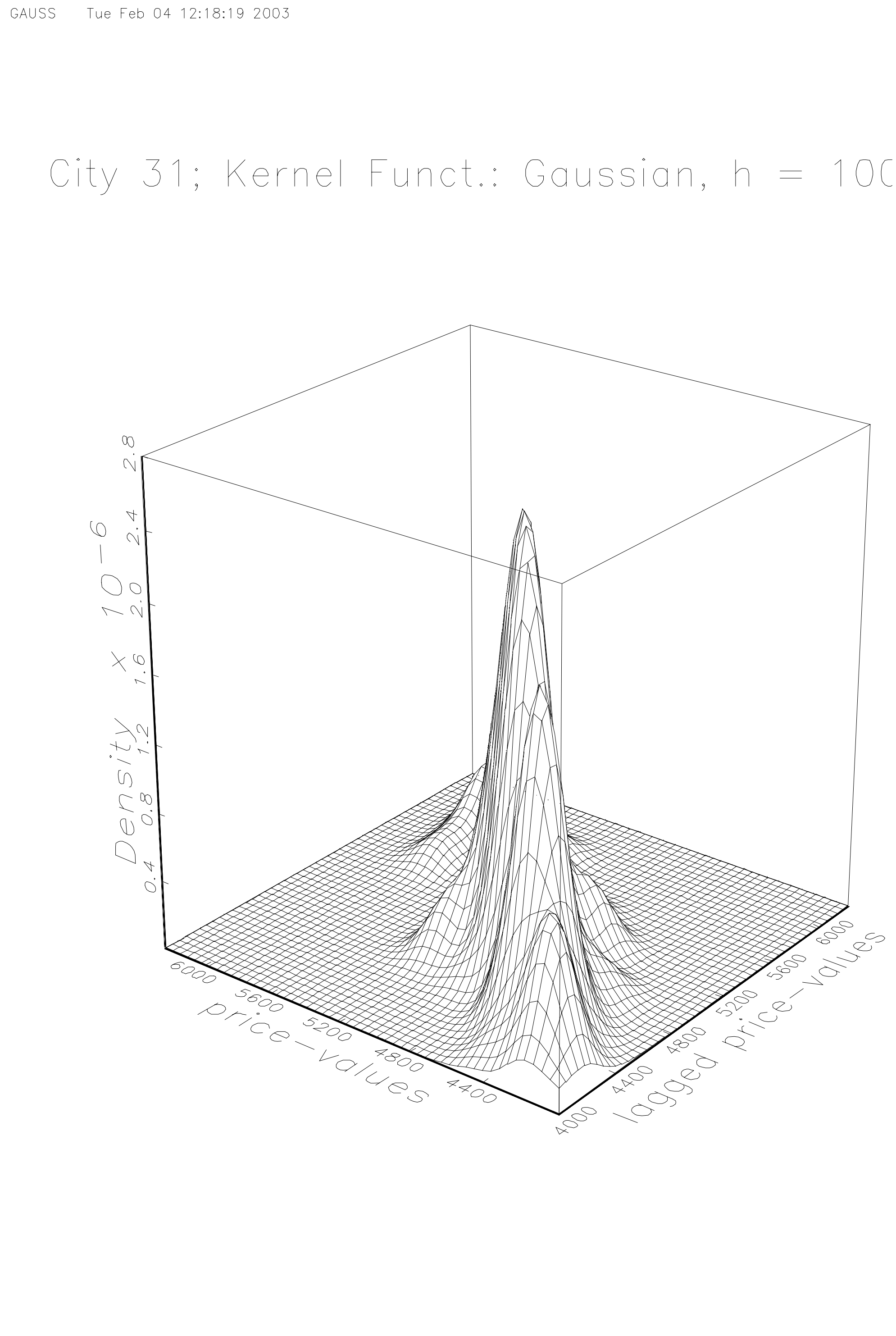
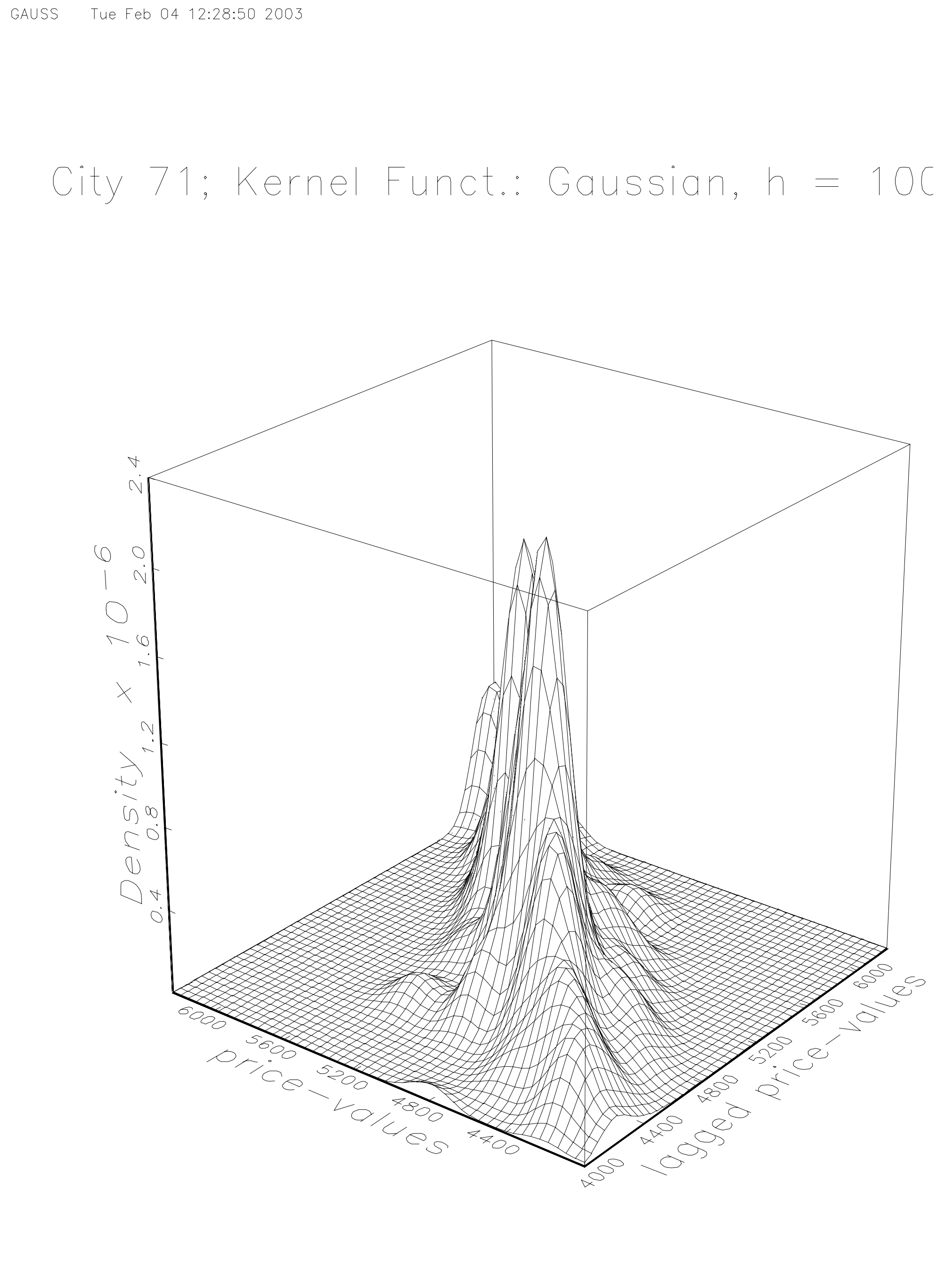


Figure 8: Graph of kernel density estimates of multivariate probability



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